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ACADEMIC PRESS
Journal of Environmental Economics and Management 45 (2003) 278–293
JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT
http://www.elsevier.com/locate/jeem

Determinants of environmental innovation in US manufacturing industries

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Received 11 November 1996; revised 20 July 1999

Abstract

This paper provides new evidence on the determinants of environmental innovation. We employ panel data models to study how environmental innovation by US manufacturing industries responded to changes in pollution abatement expenditures and regulatory enforcement during the period 1983 through 1992. We find that (1) environmental innovation (as measured by the number of successful environmental patent applications granted to the industry) responded to increases in pollution abatement expenditures, however, (2) increased monitoring and enforcement activities related to existing regulations did not provide any additional incentive to innovate. We also find some empirical evidence that environmental innovation is more likely to occur in industries that are internationally competitive.

Keywords: Environmental innovation; Endogenous technical change; Pollution abatement expenditures; Panel data

1. Introduction

Every year, US firms devote significant resources to develop new methods of reducing or treating air or water emissions, recycling or reusing waste, finding cleaner energy sources and other methods of environmental protection. Hundreds of new patents are granted every year for these environmental innovations. Yet, we know little about why firms invest in environmental research. One obvious candidate is to reduce the cost of complying with regulations. US firms are estimated to be spending between $170–185 billion annually complying with environmental regulations, an increase of about 50% over 1990 spending levels [36]. Using a general equilibrium

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0095-0696/03/$ - see front matter
doi:10.1016/S0095-0696(02)00058-X

model, Jorgenson and Wilcoxen [15] estimate that these abatement costs lowered the annual growth of US GNP by 0.2 percent per year between 1973 and 1985. Given overall annual growth rates of 2–3% per year, reductions of this magnitude are significant. Gray and Shadbegian [8] conducted a plant level analysis of compliance costs and productivity, and found that more regulated firms have significantly lower productivity levels and slower productivity growth than less regulated firms.

Given the significant regulatory and non-regulatory pressures on firms to abate pollution and the resultant cost burden, it is natural to wonder whether environmental innovation is a response to these pressures or to other market forces such as international competition and industry or economy-wide characteristics. Do firms respond to these pressures by investing in new innovative technologies that might lower the cost of environmental protection? In that regard, the literature to date is sparse. We provide new evidence on the determinants of environmental innovation by examining a panel data set that covers 146 US manufacturing industries at the three-digit SIC level from 1983 to 1992. Abatement pressures stemming from regulatory and/or other non-regulatory sources are proxied by pollution abatement costs and government monitoring activities. Innovation is proxied by the number of successful environmentally related patent applications granted to the industry. Our empirical results show that (1) there is a significant positive relationship between pollution abatement expenditures and environmental patents, however (2) there is no evidence that the frequency of government monitoring affects innovative activity. Finally, we also find some empirical evidence that environmental innovation is more likely to occur in industries that are internationally competitive.

This paper contributes to the existing literature in several ways. The limited empirical evidence to date is based either on *univariate* comparisons of abatement expenditures and innovation or on *overall* (not *environmental*) innovation. Unlike previous studies, we closely follow the industrial organization literature to explicitly model the factors that contribute to innovation and estimate the relationship between abatement pressures and *environmental* innovation in a *multivariate* regression analysis. To our knowledge, this is also the first paper that examines the relationship between government *monitoring* activities and environmental innovation.

The remainder of the paper is organized as follows. In Section 2 we present a brief review of the literature on environmental regulation and innovation and on the determinants of innovation. We present our theoretical framework and define the variables to be used in our empirical analysis in Section 3. Our empirical findings are discussed in Section 4. The final section highlights the contributions of this paper and provides suggestions for future research.

2. Prior literature on innovation

2.1. Abatement pressures and innovation

Profit-maximizing firms will always search for ways to lower the cost of doing business for a given level and quality of output. Thus, we might expect abatement pressures that raise the cost of doing business to prod firms to find lower cost methods of reducing pollution. Even this proposition, however, is not necessarily true. As McCain [23] points out, firms might be reluctant to innovate if they believe regulators will respond by ratcheting up standards even tighter. Thus, much has yet to be learned about the mechanisms that encourage firms to innovate and the extent to which innovation is likely to occur in a given industry.

Several theoretical papers have examined the linkages between abatement pressures stemming from environmental regulation and innovation. The objective of this body of literature has been to determine which environmental policy instrument (emissions charges, permits, standards, etc.) provides firms with the greatest incentive to innovate. Downing and White [6], and Milliman and Prince [24] show that the incentive to innovate is stronger under market-based systems (e.g. emission fees or permits) than under command and control regulations.

Porter and Van der Linde [29] go beyond the traditional literature by not only suggesting that environmental regulations would pressure firms to innovate, but also that ultimately this innovation could stimulate growth and competitiveness. While the latter claim is subject to much criticism and debate (e.g. [27]), the former claim is both plausible and testable. Nevertheless, the notion that environmental regulation can motivate firms to innovate has received only limited empirical scrutiny in the literature. Much of that evidence is either anecdotal or based on a limited industry case study. For example, Porter and van der Linde [29] cite several examples of companies that have gained a competitive advantage through innovation in response to more stringent environmental regulation. Burtraw [1] points out that the cost of the SO_2 permit trading system turned out to be lower than earlier estimates, at least in part because of technological innovation.

Two recent studies have begun to systematically explore the relationship between environmental regulation and innovation. Lanjouw and Mody [18] construct a patent data set from 1972 to 1986 for the US, Japan and Germany in order to study the creation and diffusion of environmental technologies. They use pollution abatement expenditures as an indicator of the severity of environmental regulations, and find that innovation follows expenditures with a 1 to 2 year lag. Although they clearly show a correlation between expenditures and patents, Lanjouw and Mody [18] neither model nor explicitly test the relationship between abatement expenditures and environmental innovation by controlling for other factors that are also likely to affect innovation.

Jaffe and Palmer [14] construct a panel data set for US manufacturing industries to determine how abatement expenditures affect innovative activities. Innovation is proxied by two different measures: total industry expenditures on R&D, and total number of successful patent applications by industry. However, the authors do not attempt to model the link between R&D and patents and instead analyze each separately. They find that higher lagged abatement costs lead to higher levels of R&D expenditure. However, when they use patent applications as an indicator of innovation, they find little evidence that they are related to abatement costs. Note that Jaffe and Palmer [14] include in their analysis *all* R&D and patents—whether environmentally related or not.

Although previous studies have largely focused on measurable abatement expenditures, regulatory pressures might also depend on government monitoring and enforcement. Increased monitoring and enforcement is likely to lead to higher abatement expenditures since many firms will not comply with regulations without the threat of penalties. However, monitoring and enforcement might also lead to environmental improvements—and innovation—even if it does not directly increase environmental expenditures. For example, environmental violators might be penalized through loss of government contracts, firm reputation or other non-market sanctions

[3,4]. Although previous empirical studies have demonstrated that increased government monitoring activity increases regulatory compliance and/or improves environmental performance of firms (see e.g. [4,21] for a survey of this literature), none have asked the related question of whether increased government monitoring or enforcement has led to innovation.

Not all abatement pressures are regulatory in nature. Indeed, there is growing evidence that firms respond to other external pressures for voluntary overcompliance such as local/interest group pressures, customer demand or other social pressures (see e.g. [17,20]). While the mechanisms through which these pressures operate upon a firm might vary, in many cases, they are likely to raise at least the short-run cost of doing business. To the best of our knowledge, there are no existing studies that have explicitly analyzed the impact of these external pressures on innovation.

2.2. *Other determinants of innovation*

A number of studies in the industrial organization literature have focused on the determinants of innovation in general. Their findings are relevant for modeling environmental innovation. The cornerstone of this body of work is the contentious Schumpterian conjecture of a positive relationship between market power and innovation, and that large firms are more innovative than small firms [34]. Proponents of this view argue that monopolists enjoy superior access to capital, ability to pool risks, and economies of scale in maintaining R&D laboratories. For example, Scherer [31] and Mansfield [22] find a positive relationship between industry concentration and innovative activity. However, opponents argue that highly concentrated industries face less competitive pressure to innovate, while industries with a lot of firms investing in R&D are more likely, through chance alone, to discover successful innovations. For example, Williamson [38] and Geroski [7] find that concentration has a dampening effect on innovation. Thus, the overall impact of market structure on innovation is ambiguous. Other determinants of innovation at the industry level include capital intensity [13,32] and industry-specific technological "opportunities" [5].

Finally, there is some evidence that foreign competition might spur innovation. Hughes [13] finds that if foreign markets are more responsive to variety, increases in export intensity lead to increases in R&D. In the context of environmental technologies, Scott [35] finds that R&D investments in air emission controls by US manufacturing firms increased in response to foreign competition. Porter and Van der Linde [29] also suggest that world demand is moving in the direction of valuing low-pollution and energy-efficient products and processes. Thus, they speculate that internationally competitive industries are more likely to innovate in response to environmental regulation than industries that are uncompetitive to begin with.

3. Model and data

Our objective is to study the nature of the relationship, if any, between abatement pressures and innovation. In modeling this relationship, we closely follow the existing industrial organization literature on innovation [5,7] and add two new variables to incorporate the effect of abatement pressures on innovation. In particular, we estimate the following reduced form equation:

$$\begin{aligned}(\text{PATENTS}_{i,t}) = {} & \alpha_i + \gamma_t + \beta_1(\text{PACE}_{i,t}) + \beta_2(\text{VISITS}_{i,t}) + \beta_3(\text{VALSHIP}_{i,t}) \\ & + \beta_4(\text{CONC}_{i,t}) + \beta_5(\text{CAPINT}_{i,t}) + \beta_6(\text{EXPINT}_{i,t}) + \varepsilon_{i,t}\end{aligned} \tag{1}$$

where i indexes industry, t indexes time, PATENTS is the number of successful patent applications, PACE is the pollution abatement expenditure, VISITS is the number of air and water pollution related inspections, EXPINT denotes export intensity, VALSHIP is the value of industry shipments, CONC is industry concentration, CAPINT denotes capital intensity, α_i captures unobservable industry heterogeneity, γ_t represents time effects, and $\varepsilon_{i,t}$ is a residual error term capturing all other effects. We do not impose a lag structure in this model because the literature suggests that the lag between R&D expenditure and patent application filing is not very large.[1] The variables used in the model presented above are described next. We describe variations of this basic model to check for robustness of our specification in Section 4.

3.1. *Environmental innovation*

Consistent with earlier studies, we use successful patent applications (PATENTS) as a proxy for environmental innovation.[2] Unlike previous studies, however, we measure *environmental* patents. These data were compiled from a database maintained by the Office of Technology Assessment and Forecast of the United States Patent and Trademark Office. Patents involving hazardous or toxic waste destruction or containment, recycling or reusing waste, acid rain prevention, solid waste disposal, alternative energy sources, air pollution prevention and water pollution prevention were counted as "environmental patents." The SIC industry to which each of these patents belongs was determined based on the primary line of business of the organization that is named first on the patent application.[3] A total of 3680 environmental patents were identified over the 10-year period 1983-1992, about 370 per year.

[1] Hall et al. [10] found that the relationship between R&D and patent applications was close to contemporaneous with some lag effects that were small and not well estimated. Griliches [9] observed that this is consistent with the observation that patents tend to be taken out early in the life of a research project. Furthermore, our overall conclusions were not significantly altered when we re-estimated Eq. (1) using 1 and 2 year lags on the exogenous variables.

[2] There are two potential problems with using patents as a proxy for innovative activity. First, although we assign patents to the industry of origin, they might be more appropriately assigned to the industry of use (if different). We do not know the industry of ultimate use—only the industry that originates the patent. However, this problem is also inherent in using R&D expenditures. Second, the economic significance of a higher number of patents is not clear in the sense that some patents may be worth more than others. Nevertheless, patent counts are suitable for our application because we are primarily studying whether industries that are faced with heightened abatement costs engage in research as a *potential* way of reducing those costs.

[3] There will be some misclassification if an organization is granted a patent for a product or process different from its primary line of business. Unfortunately, the Patent Office does not ask applicants to identify themselves by industry, and there is no literature suggesting a better way to aggregate patent data to the industry level.

3.2. Abatement pressures

Since no direct measure of "abatement pressures" exists, we employ two proxies in this study: pollution abatement costs (PACE) and government inspections and monitoring activities (VISITS).

3.2.1. Pollution abatement and control expenditures (PACE)

The Census Bureau conducted the Pollution Abatement Cost and Expenditure (PACE) survey annually between 1973 and 1994 (except for 1987). The survey collected information on both pollution abatement capital and operating costs incurred by manufacturing firms.[4] Following Gray and Shadbegian [8], operating cost data is used instead of capital expenditure because it has fewer missing values. PACE operation and maintenance costs include salaries and wages, fuel and electricity, materials, contract work and services, depreciation of abatement capital, and payment to governmental units for sewage collection and solid waste collection and disposal. The survey forms and instructions explicitly state that expenditures for research and development should not be counted as abatement costs. Since the survey was not conducted in 1987, PACE values for that year are interpolated.[5]

Previous research has focused on PACE as a measure of regulatory burden (e.g. see [8,14]) under the assumption that when regulations are tightened, firms will spend more on abatement. Although we expect PACE to increase when regulations are tightened, other factors might also cause PACE to increase. For example, external pressures from interest groups or customers might cause firms to increase their abatement expenditures in an attempt to maintain a good environmental reputation. Thus, if firms overcomply with existing regulations this could also be reflected in increased PACE. However, we do not distinguish between regulatory and overcompliance pressures, and instead focus on their combined effect in our analysis since data at that level of detail are unavailable. Regardless, it is unclear why the incentives for innovation would be any different if the pressures were for regulatory compliance or overcompliance.

Factors other than abatement pressures are also likely to affect PACE, however. For example, abatement expenditures for a given industry can change over time because of expansion and contraction of output over business cycles. Similarly, expenditures across industries can differ because of unobserved heterogeneity, such as type of output, productivity, and accounting practices. We control for this by introducing industry- and time-specific effects into our model.

Despite the fact that many researchers rely upon PACE in empirical studies of the cost of pollution control, there is growing concern about its reliability, use and interpretation. Industry reported expenditures could *understate* true costs if overhead and managerial costs are excluded; investment in more efficient facilities is discouraged due to new source bias [26]; abatement efforts result in the crowding out of other productive investments and R&D [33]; and operational

[4] The survey covers approximately 17,000 establishments with 20 or more employees. Though the survey is conducted at the firm level, only data aggregated at the two-, three- and four-digit SIC code is available to the public.

[5] Our main results are unaffected if we drop observations from 1987 instead of using interpolated estimates of abatement costs.

flexibility is lost [16].[6] On the other hand, reported expenditures can also *overstate* true costs if there are complementarities between abatement and other productive activities and because of induced technical change [29].[7] Abatement costs are also self-reported by industry and are hence subject to manipulation. To the extent firms want to convince regulators they are imposing an undue burden upon industry, PACE expenditures might be systematically overstated. Empirically, the debate is still ongoing. Recently, Morgenstern et al. [25] have examined a panel data set covering more than 800 manufacturing plants over the period 1979 through 1991 to address the question of whether reported expenditures accurately measure the cost of environmental regulations. They estimate a cost function model with fixed effects to account for productivity differences across plants and find no statistically significant evidence of either over- or understatement of true costs.

Even if PACE represents an over- or understatement of true costs, we would be able to use these data for our purposes. We are primarily interested in the effect of changes in expenditures on innovation—not in the level of expenditures. If industries respond to heightened abatement costs by engaging in more research, we would expect a positive sign on β_1, the coefficient of the pollution abatement cost variable (PACE).

3.2.2. Government monitoring (VISITS)

Our second measure of abatement pressure is government monitoring activities. As noted in the previous section, while increased monitoring and enforcement is likely to lead to higher abatement expenditures, it might also affect firms by other non-market mechanisms or by imposing costs outside the pollution abatement arena (e.g. loss of reputation or of government contracts). Thus, while VISITS might be correlated with PACE, we are interested in measuring any independent effect of monitoring on innovation.

To the extent that stricter government monitoring or enforcement induces firms to comply, they might now seek less costly methods of complying. Thus, stricter monitoring and enforcement might spur innovation as well. On the other hand, since there is evidence that EPA targets industries with compliance problems, stricter monitoring and enforcement might have little effect on innovation as firms in that industry step up their immediate compliance efforts by adopting existing controls. These firms might not be able to wait for the time and uncertainty associated with innovative activity. Thus, whether or not increased government enforcement and monitoring has an effect on innovation is an empirical issue.

Data on the number of air and water pollution related inspections at the industry level was obtained from the Environmental Protection Agency under a Freedom of Information Act request. The data include all types of inspections (e.g. compliance evaluations by Federal, State and local agents, reconnaissance, pretreatment audits, diagnostic checks, etc). If innovation within an industry is spurred by increased inspections related to existing air and water regulations, we would expect a positive sign on β_2, the coefficient of the inspections variable (VISITS). On the

[6] General equilibrium analyses, such as Jorgenson and Wilcoxen [15], have also drawn a distinction between "abatement expenditures" and "social costs". The latter include spillover effects and welfare changes associated with the regulation.

[7] A related branch of the literature has found that ex-ante cost estimates often exceed ex-post measures of the cost of a given regulation (see [11,28]).

other hand, if increased monitoring reflects a lack of compliance history in an industry, that industry might have little resources available for innovative activities, and we could observe a negative sign on β_2.

3.3. Other control variables

Following the industrial organization literature on innovation, we include control variables shown elsewhere to be important determinants of innovation. Unless otherwise noted, data on industry variables were obtained from the Annual Survey of Manufacturers published by the US Department of Commerce.

An industry with higher abatement expenditures or inspections may also have higher patenting activity simply because it is larger in size. Thus, we control for industry size by including industry level value of shipments (VALSHIP) as an additional explanatory variable in Eq. (1). Since larger industries might be better suited to bear the high fixed costs and risks involved in research, we expect the coefficient of the value of shipments variable (β_3) to be positive.

Market structure might also affect innovative activity. The four-firm concentration ratio (CONC) is used in our analysis as an indicator of market structure.[8] These ratios were computed from annual sales figures reported in the Ward's Business Directories. The sign of the concentration (CONC) coefficient, β_4, is hard to predict given the debate surrounding the Schumpeterian conjectures. Based on the literature, we expect to see a small and possibly insignificant coefficient for concentration when industry fixed effects are used to control for unobservable differences in technological opportunity.

Capital intensity (CAPINT) might also affect innovation within an industry.[9] However, given the ambiguity in the literature, the sign of β_5, the coefficient for capital intensity (CAPINT), is difficult to predict.

The export intensity (EXPINT) variable takes into account the influence of trade on environmental research. Export intensity is measured as the ratio of export related shipments to total shipments in an industry, taken from data published by the Foreign Trade Division of the US Department of Commerce. These data are only available at the two-digit SIC level for the period in question. Thus, we use data at the two-digit SIC level as a proxy for export intensity at the three-digit SIC level. To the extent that foreign markets are competitive and product variety is valued, we expect more innovation in export intensive industries. In particular, if a significant number of consumers in foreign countries demand green products, then the opportunity of reaching more customers or charging premium prices via exports could make environmental R&D more attractive. Thus, we would expect a positive sign on β_6, the coefficient for EXPINT.

The number of successful patent applications by an industry can also be affected by other unobservable exogenous factors (α_i). Chief amongst these factors is the "technological opportunity" available to the industry. In the fixed effects specification, this industry heterogeneity is assumed to be relatively constant in the short and medium run and is represented

[8] Several other indicators such as the Herfindahl index, the number of small firms in the industry, and the market share held by existing firms in the industry, have been proposed in the literature. We will not include them all because of possible collinearity problems. Furthermore, none of these other variables have displaced the standard concentration ratios.

[9] Capital intensity is measured as the ratio of new capital expenditure to total shipments in an industry.

Table 1
Summary statistics for all industries

Variable	Measurement	Mean	Standard deviation	Min	Max
PATENT	Number	2.69	8.26	0	81
PACE	Million dollars	98.2	245.7	0	2744
VISITS	Number	150.5	269.7	0	2810
EXPINT	Percent	13.82	7.64	2.2	34
VALSHIP	Million dollars	18052	25375	47	239120
CONC	Ratio	0.39	0.18	0.10	1
CAPINT	Ratio	0.03	0.02	0.0005	0.55

The number of observations used in the computation is 1409.

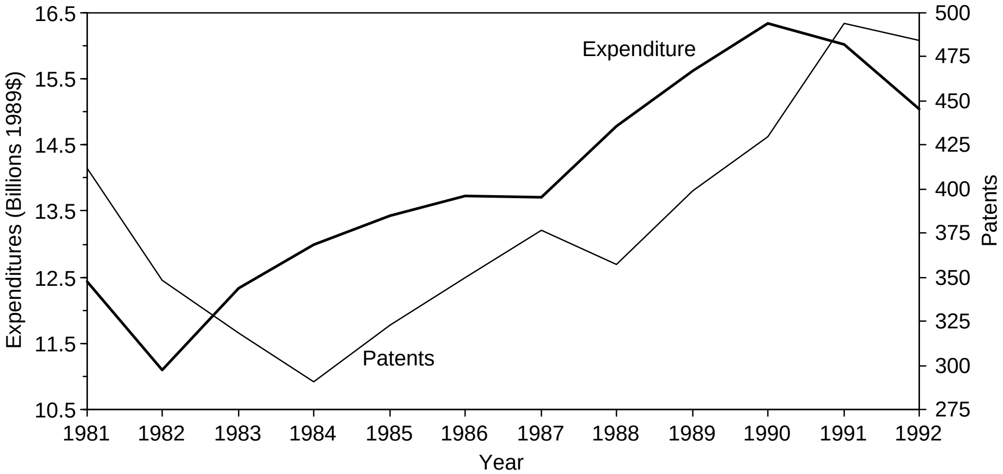

Fig. 1. Pollution abatement expenditures and environmental innovation.

by a set of industry dummies. In contrast, industry heterogeneity is allowed to vary randomly across industries in the random effects specification.

Finally, we include a set of year dummies to account for period specific events, such as recessions, that could have economy-wide implications for patenting activity.[10]

4. Empirical results

Table 1 presents the mean, standard deviation, minimum and maximum value across all industries and years, for each variable used in our study. As a first step, we begin by graphing our data on US environmental patent applications, abatement expenditure and monitoring for the period 1981–1992. Fig. 1 depicts the historical trends in the level of patent applications and pollution abatement expenditure in the US, and indicates that innovation follows expenditures

[10] The base year is 1983.

with about a 1 year lag. This is consistent with Lanjouw and Mody [18] who arrive at a similar conclusion by using earlier data from the period 1972–1986. Fig. 1 also suggests that both patents and abatement expenditures rose during the expansion years and fell during recession years. However, the decline in abatement expenses during the early 1980s need not have stemmed entirely from the recession. During the early years of the Reagan administration, EPA Administrator Ann Gorsuch also initiated a scaling back in the implementation and enforcement of several environmental programs [37]. Nevertheless, Fig. 1 indicates that we should control for time-specific effects in our model.

Unlike Fig. 1 that suggests a positive correlation between abatement expenditures and innovation, the relationship, if any, between monitoring effort and innovation is unclear from Fig. 2. There appears to be a negative relationship during the early and late 1980s, and a weak positive relationship in the mid-1980s.

Of course, Figs. 1 and 2 are simple correlations and do not capture the richness of the model presented in the previous section. Our main results, using multivariate regression analyses, are reported in Table 2. Our data cover 146 industries over the 10-year period 1983–1992. We exploit the time-series and cross-sectional nature of the data by using panel data estimation techniques to obtain estimates that are more efficient than those based only on time-series or cross-sectional analysis.

We first estimate a linear fixed effects model (Model (1)), since unobservable factors that are constant over time but vary across industries can influence patenting. The linear fixed effects model is given by $y_{i,t} = \alpha_i + \gamma_t + X_{i,t}\beta + \varepsilon_{i,t}$, where y is the dependent variable, X is the vector of explanatory variables, α_i are the industry-specific intercept terms, γ_t are the time effects, and $\varepsilon_{i,t}$ is a random disturbance term. In this model, all permanent inter-industry variation in patenting activity is captured in the coefficients of the industry-specific dummies. Thus, the coefficients of other explanatory variables in the fixed effects model only reflect the relationship between patenting activity and these other variables in the within-industry across time dimension. An

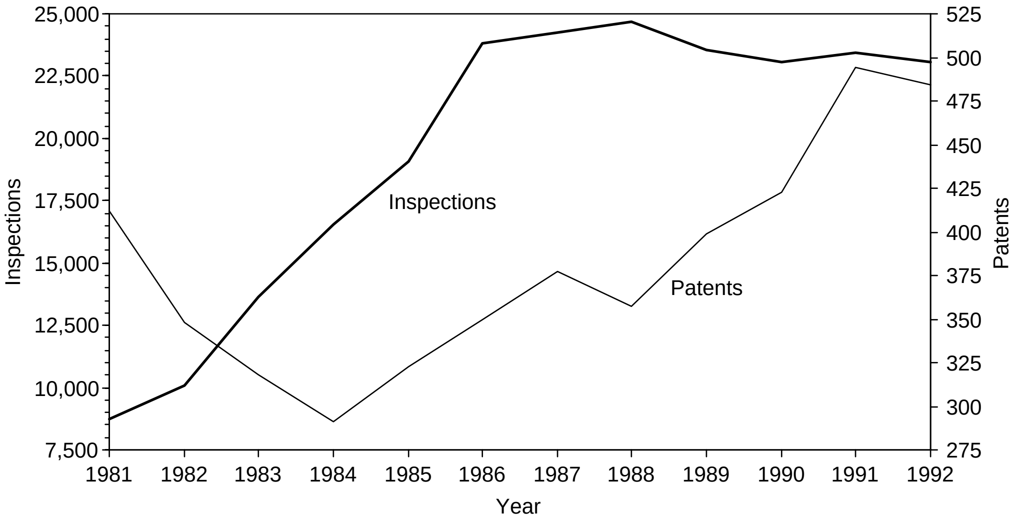

Fig. 2. Monitoring and environmental innovation.

F-test rejects the null hypothesis that the industry-specific dummies are all equal. This suggests that inter-industry differences such as variations in technological opportunity play a major role in explaining variation in patenting activity. Hence, a pooled OLS model ignoring industry heterogeneity would suffer from omitted variable bias.

We also estimate a Poisson count data model (Model (2)) since our dependent variable, the number of successful patent applications $y_{i,t}$, is a non-negative integer. The Poisson distribution is characterized by equidispersion, wherein a single parameter $\lambda_{i,t} = \alpha_i \exp(X_{i,t}\beta)$ is equal to both the conditional mean, $E(y_{i,t}|X_{i,t})$, and the conditional variance, $V(y_{i,t}|X_{i,t})$. Cameron and Trivedi [2] note that equidispersion of count data is not necessary for consistent estimation of the coefficients as long as the conditional mean is correctly specified. However, overdispersion will cause the computed maximum likelihood t statistics to be inflated due to an underestimation of the standard errors. Thus, we use the method of generalized estimating equations [19] in lieu of conditional maximum likelihood to obtain ''semi-robust'' standard errors that are adjusted for clustering by industry group.

An indication of overdispersion can be obtained by comparing the sample mean and variance. In our case, the raw patent count data are highly overdispersed with a sample mean of 2.7 and a variance of 68. An alternative to the Poisson is to specify a more general discrete distribution that ensures non-negativity but does not impose equidispersion. A common choice is the Negative Binomial distribution with conditional variance assumed to be a function of the conditional mean, and conditional mean equal to $(\alpha_i/\delta_i)\exp(X_{i,t}\beta)$. The parameter α_i is the unobserved industry heterogeneity and δ_i is the dispersion parameter, both of which are permitted to vary across industries. We estimate this model under both the fixed and random effects specification.

The Negative Binomial fixed effects model assumes that the dispersion varies across industries but is constant over time. The model is estimated by conditioning on the sum of the patent counts over time for each industry, as described in [12]. The estimated results for the Negative Binomial fixed effects specification are presented under Model (3) of Table 2. In contrast, the dispersion is allowed to vary randomly across industries in the Negative Binomial random effects model. The model is estimated by maximum likelihood and the results are presented under Model (4) of Table 2.

As shown in Table 2, our key results are qualitatively robust across the four models. The magnitude of the coefficients does vary though. Thus, we will discuss the estimation results primarily in terms of our preferred model, the Negative Binomial random effects, since it accounts for overdispersion and performs well in terms of predicted values.[11]

The coefficient for PACE is significant and positive in all models. Even after controlling for other factors, we find a positive association between pollution abatement expenditures and environmental innovation over time. Since Model (4) is a non-linear specification, the PACE coefficient of 0.0004 represents the semi-elasticity of patents with respect to PACE. Specifically, mean patents are expected to increase by 0.04 percent when industry abatement expenditures increase by \$1 million (and other variables are held constant). Thus, we estimate that the magnitude of this impact is economically small but statistically significant. This further confirms our preliminary findings in Fig. 1 as well as the findings of Lanjouw and Mody [18]. This result

[11] The mean number of patents predicted by the linear fixed effects model is the closest to the true mean, but the predictions are not restricted to non-negative integers.

Table 2
Effect of abatement pressures on environmental innovation

Variable	Model (1) linear, fixed effects	Model (2) Poisson, population averaged	Model (3) Negative binomial, fixed effects	Model (4) Negative binomial, random effects
PACE	0.0125	0.0005	0.0005	0.0004
	(0.000)***	(0.004)***	(0.044)**	(0.045)**
VISITS	−0.0025	−0.0002	0.0004	0.00009
	(0.109)	(0.760)	(0.388)	(0.822)
VALSHIP	0.00005	0.0000007	0.0000005	0.0000005
	(0.002)***	(0.000)***	(0.012)**	(0.004)***
CONC	−0.6395	−0.8963	0.1067	−1.086
	(0.477)	(0.027)**	(0.779)	(0.004)***
CAPINT	4.6501	1.4138	1.581	1.1211
	(0.270)	(0.016)**	(0.065)*	(0.199)
EXPINT	0.0307	0.0180	0.0598	0.0237
	(0.414)	(0.214)	(0.000)***	(0.086)*
1984	−0.3314	−0.1545	−0.023	−0.1286
	(0.283)	(0.299)	(0.874)	(0.265)
1985	−0.1634	−0.0481	0.0680	−0.0304
	(0.591)	(0.767)	(0.651)	(0.800)
1986	0.1020	0.1183	0.1672	0.099
	(0.749)	(0.376)	(0.283)	(0.439)
1987	0.1365	0.1082	0.0625	0.0219
	(0.696)	(0.408)	(0.710)	(0.880)
1988	−0.1577	0.0499	−0.0015	0.0154
	(0.646)	(0.735)	(0.992)	(0.908)
1989	−0.1509	0.1014	−0.1151	0.0023
	(0.685)	(0.495)	(0.478)	(0.987)
1990	−0.1820	0.0899	−0.1316	0.0639
	(0.656)	(0.531)	(0.452)	(0.708)
1991	0.2977	0.2642	−0.0837	0.2121
	(0.504)	(0.067)*	(0.652)	(0.270)
1992	0.1578	0.2249	−0.2175	0.1169
	(0.728)	(0.092)*	(0.235)	(0.545)
R^2	0.9206	—	—	—
Log likelihood	—	—	−1111.16	−1542.75
Mean predicted patents	2.69	0.59	1.09	2.34

(1) The dependent variable is PATENTS. The regression coefficients are in the upper rows; p-values are in lower rows (in brackets).
(2) Model (1) is estimated using the within regression least-squares method. Model (2) is estimated using the generalized estimating equation method that provides semi-robust standard errors adjusted for clustering by industry. Model (3) is estimated using conditional maximum likelihood and Model (4) is estimated using maximum likelihood estimation.

***Indicates significance at $p<0.01$.

**Indicates significance at $p<0.05$.

*Indicates significance at $p<0.10$.

also builds on Jaffe and Palmer [14], who find that lagged abatement expenditures have a significant positive effect on overall R&D expenditure but an insignificant effect on patenting when they control for industry fixed effects. The authors model these two effects separately and do not speculate why increased R&D expenditure fails to translate into increased patents. In contrast, we find evidence of a small, positive impact of abatement expenditures on patenting by concentrating on environmental (and not overall) innovation and using more disaggregated data.

The VISITS coefficient in our analysis is insignificant across all models, which is also consistent with our preliminary findings based on Fig. 2. One explanation is that VISITS might be insignificant if it is highly correlated with PACE. However, the Pearson correlation coefficient between VISITS and PACE is only 0.43. Furthermore, the VISITS coefficient remains insignificant when we re-estimate the model after excluding the PACE variable. Thus we are unable to find any evidence that increased monitoring provides any independent incentives for innovation through, for example, direct or reputational penalties.

The control variables generally have the expected sign. The coefficient for VALSHIP is positive and highly significant in all models indicating that there is a positive relationship between industry output and patenting activity. The coefficient for CONC is negative and significant in Model (4) suggesting that innovation is linked positively to domestic competitiveness. However, this coefficient becomes insignificant in Models (1) and (3), which is consistent with earlier findings in the industrial organization literature that market structure has a smaller impact on innovation when industry fixed effects are included in the model. The coefficient of EXPINT is positive and significant in Models (3) and (4), consistent with the notion that foreign demand for greener products spurs environmental innovation. Model (4) indicates that a unit (1 percent) increase in export intensity leads to a 2.4 percent increase in expected patents. No significant patterns associated with across-the-board changes in environmental policy or economic conditions are discernable from the coefficients of the time dummies.

These basic results are robust to several variations in the model specifications shown in Table 2, including: the use of 1 and 2 year lags on the exogenous variables; the exclusion of CONC and CAPINT; the inclusion of only one "regulatory stringency" variable (PACE or VISITS) at a time; estimation of separate regressions by year in lieu of a panel data model; and estimation of a panel data model after aggregation of all variables to the two-digit SIC level.[12]

5. Conclusions

This paper investigates the relationship between pollution abatement pressures (proxied by changes in abatement costs and monitoring) and environmental innovation. A model of innovation is estimated using a panel dataset of 146 US manufacturing industries tracked from 1983 to 1992. We find that, other things held constant, increases in pollution abatement expenditures are associated with a small, but statistically significant increase in environmental innovation (as measured by successful environmental patent applications). This is consistent with

[12] The last specification was estimated because data on one of the variables, EXPINT, was only available at the two-digit SIC level.

the basic insights into the innovation process formulated by Schumpeter, as well as previous limited empirical evidence on abatement expenditures and patents [14,18].

Although we can only speculate why the magnitude of our estimated effect is so small—about a 0.04 percentage increase in patents per $1 million in pollution abatement expenditures—we note that our patent data exclude those innovations that are developed in academia or in the non-manufacturing sectors. In addition, our analysis is a very conservative approach in that it ignores the effect of industry-constant abatement expenditures on patents. Thus, or example, the fact that one industry has a high PACE relative to industry-wide capital expenditures might induce firms in that industry to seek more environmental patents. However, that effect would be captured in the industry heterogeneity variable in our regression analysis. We also note that firms might be reluctant to invest in R&D for fear that regulators will ratchet up the standards once new technologies have been developed that lower the regulatory burden [23].

Although increased abatement pressures appear to increase patents, we find no evidence that an increase in monitoring effort motivates innovation. Finally, we find moderate empirical support for a positive relationship between the international competitiveness of an industry and its innovative activity. Industries that have higher levels of foreign competition tend to have more environmental patents.

It is important to note that our finding that environmental innovation occurs in response to increases in abatement costs does not necessarily imply that net profits increase. It is quite possible that despite these new innovations, there are high opportunity costs to diverting resources towards environmental R&D. For example, Robinson [30] finds that EPA and OSHA regulations divert economic resources and managerial attention away from productivity-enhancing innovation. In that case, an increase in environmental innovation would not be expected to lead to an overall increase in future competitiveness.

Our findings suggest the need for further research in understanding the relationship between abatement pressures, innovation and competitiveness. A natural extension of our results would be to determine if the increased innovation leads to increases or decreases in industry profitability. It would also be useful to conduct a patent study using more disaggregated plant level data. The issue of inter-country differences in environmental regulation and patenting activity also merits examination. But these are all tasks for the future.

Acknowledgments

The authors thank William Brown (US Patent Office), Bruce Rothrock (US Environmental Protection Agency) and Karen Palmer (Resources for the Future) for generously providing data. We also thank the anonymous referees, Seema Arora, Sharon Barrell, Markus K. Brunnermeier, J. S. Butler, and Clifford S. Russell for helpful comments. The usual disclaimer applies.

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